

The Problem of Carbon Dioxide

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INTRODUCTION

Decisions on future energy supply systems should be made with regard to the alternatives available. Therefore, information is needed on the risks and benefits of these systems. The risks of nuclear power have been discussed at great length; in this discussion, nuclear power has played the role of a symbol expressing concern about technological development in general Ref [1]. However, to arrive at rational decisions, nuclear power has to be seen in perspective, i.e., with regard to the benefits and the risks of the alternatives. One of the risks of possible long-term global concern is the emission of carbon dioxide (CO₂) from fossil fuel consumption.

MEASUREMENTS OF ATMOSPHERIC CO₂-CONCENTRATIONS

During the past century a steady increase in the atmospheric carbon dioxide concentration has been observed. The most reliable systematic data have been developed at Mauna Loa (Hawaii) and cover the period from 1958. They are displayed (in part) on the cover of this issue of the Bulletin. The seasonal variations are caused by the natural cycle of plant growth and decay, variations of solubility in surface ocean water and variations in emissions from energy production. Therefore, the maxima occur during spring time. The variations decrease with altitude and increase with northern latitude. Figure 1 indicates that CO₂-concentrations have been monitored worldwide Ref [2]. The increase in the southern hemisphere follows the northern increase with a time delay of about 2 years.

Earlier data are not as reliable. However, they suggest that the pre-industrial level of atmospheric CO₂-concentration was about 295 ± 5 ppm by volume. Thus an increase of more than 10% has occurred since the beginning of industrialization.

WHY IS CARBON DIOXIDE A PROBLEM?

At the levels discussed here, CO₂ is not toxic and one should not confuse it with the highly toxic carbon monoxide. On the contrary, CO₂ increases plant growth as it provides, together with water, the basic materials needed for photosynthesis. The principal risk of an increase in atmospheric CO₂-concentration is its impact on the radiation balance of the atmosphere, the so-called "greenhouse" effect.

As the reflectivity (albedo) of the atmosphere is about 29%, the theoretical equilibrium temperature can be calculated as -19°C , or 34°C less than the observed average of about $+15^{\circ}\text{C}$. This important difference, which is necessary for life on earth, is caused by the fact that the atmosphere provides a window (48% transparent) for the incoming solar radiation but absorbs (20% transparent) the infrared radiation emitted from the earth's surface. Thus the atmosphere acts as a blanket to keep the earth warm. This effect is similar to the role

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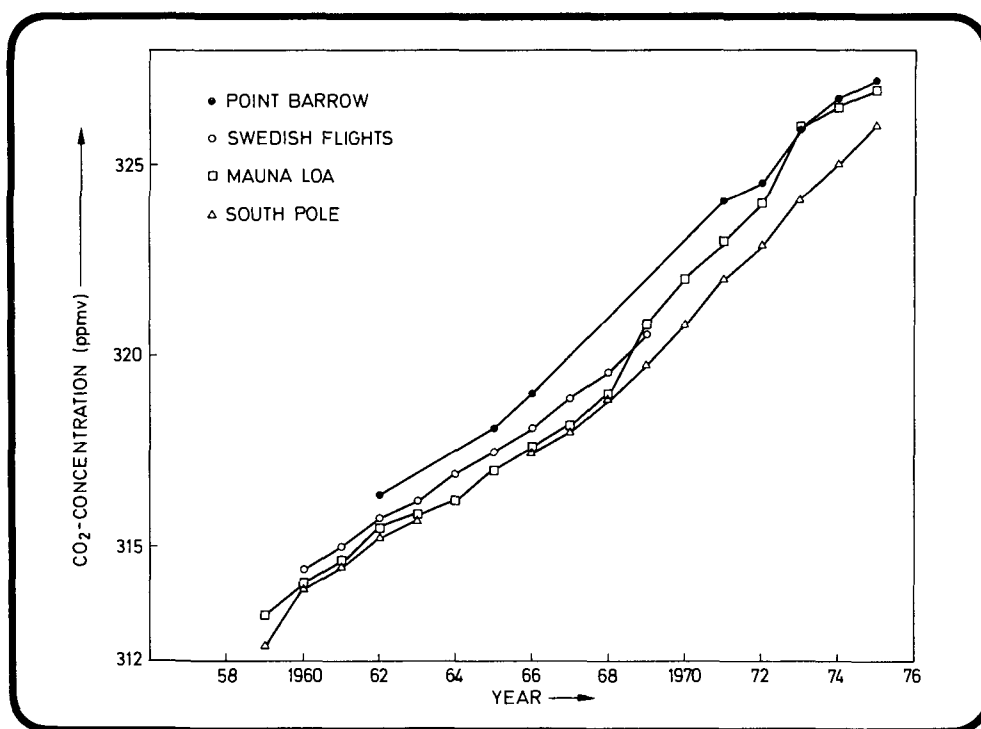
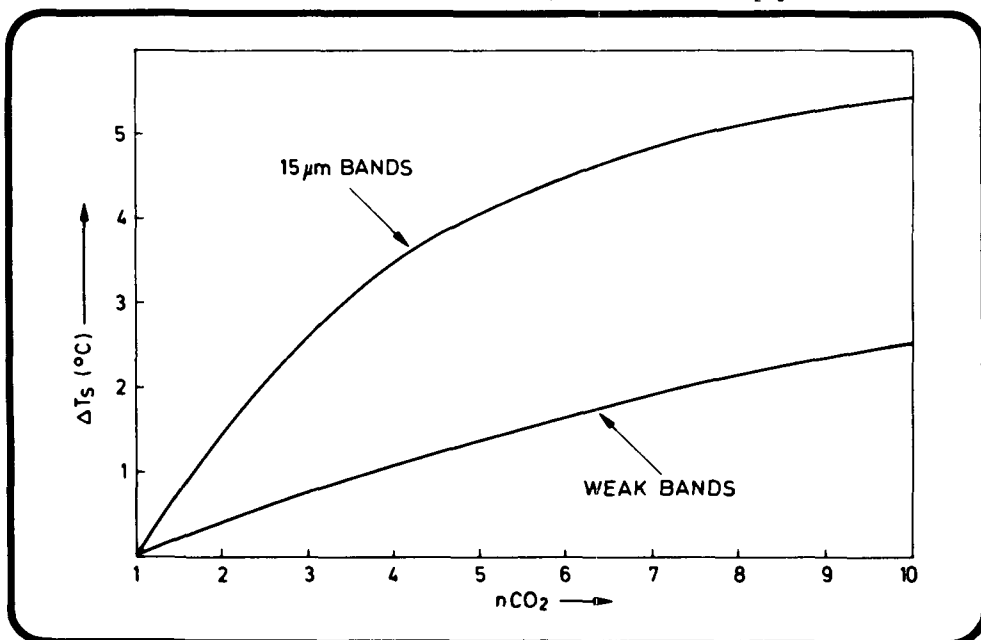


Figure 1. Global increase of atmospheric CO₂ Ref. [2].

Figure 2. Temperature effect of increasing atmospheric CO₂-concentrations. Both contributions sum to 1.98°C per doubling. (2 nCO₂ = 640 ppm) Ref. [3].



glass roofs play for greenhouses, after which this effect has been named. It is mainly caused by water vapour and carbon dioxide.

Models simulating this behaviour of the atmosphere have been used to calculate the effects of a change in carbon dioxide concentration. All calculations agree quite well that the temperature increase due to a doubling of atmospheric CO₂-concentration will be between about 2°C and 3°C, depending on assumptions about other parameters (fixed cloud-top altitude or fixed cloud-top temperature). Figure 2 shows the lower estimate of a temperature response plotted against CO₂-concentrations Ref. [3]. It shows contributions of two absorption bands, with one levelling off at higher concentrations. Up to a doubling of atmospheric CO₂-concentration the response curve is almost linear.

These data refer to temperature changes in the lower troposphere. Figure 3 shows that the temperature change decreases with altitude and even becomes negative beyond a height of about 10 km Ref. [4]. This relationship has been a point of great confusion in the past as it had been pointed out Ref. [5] that today's CO₂-concentration would already absorb 98.5% of the radiation in the relevant absorption bands. This led to the wrong conclusion that the CO₂-effect could only be minimal. However, Figure 3 demonstrates that although this is true for the total atmosphere, a significant warming occurs in the lower troposphere because for a doubling of CO₂-concentration only half the pathlength is required for the same absorption.

The data given in Figure 2 are representative for low and middle latitudes. The more stable conditions in polar and subpolar regions require that an amplifying factor of about 3 be considered Ref. [6] for these latitudes.

WHAT CAUSES THE INCREASE IN ATMOSPHERIC CARBON DIOXIDE?

Some hundred million years ago solar energy was stored in the form of organic compounds by photosynthesis. By combustion of fossil fuels this energy is released, mainly by the conversion of carbon into carbon dioxide. Specific emissions range from 3.4 tons of carbon dioxide per ton of coal equivalent for lignite to 1.9 t CO₂/t of coal equivalent for natural gas. They can be used to calculate total emissions. These emissions into the atmosphere are at present about 20×10^9 t CO₂ per year and the amount emitted since 1850 totals about 500×10^9 t of CO₂. The carbon dioxide in the atmosphere (about 2600×10^9 t) is continuously in exchange with the carbon stored in seawater (100 m surface layer stores about 840×10^9 t carbon, deep ocean water about $36\,000 \times 10^9$ t carbon and 830×10^9 t in organic matter) and the carbon stored in biomass on land (about 1500×10^9 t carbon). Because of their respective molecular weights, 12 g of carbon are equivalent to 44 g of carbon dioxide. As about 50% of the emitted CO₂ remains in the atmosphere it is assumed that most of the balance is absorbed by the oceans. This has been confirmed by several calculations with models of the global carbon cycle. However, recent measurements of carbon-13 concentrations in tree-rings seem to indicate that in addition to these emissions from fossil fuel consumption an input of CO₂ into the atmosphere might have occurred due to large scale deforestation. These calculations are not very reliable, as only several trees have been measured, data on deforestation are only extrapolations from very limited areas and no process is known which could account for the additional uptake of CO₂ by the oceans which then must have occurred.

Therefore, the following calculations are based on a model Ref. [7] of the global carbon cycle which has to assume, like other models Ref. [8], a slight increase in plant growth due to higher assimilation rates by plants.

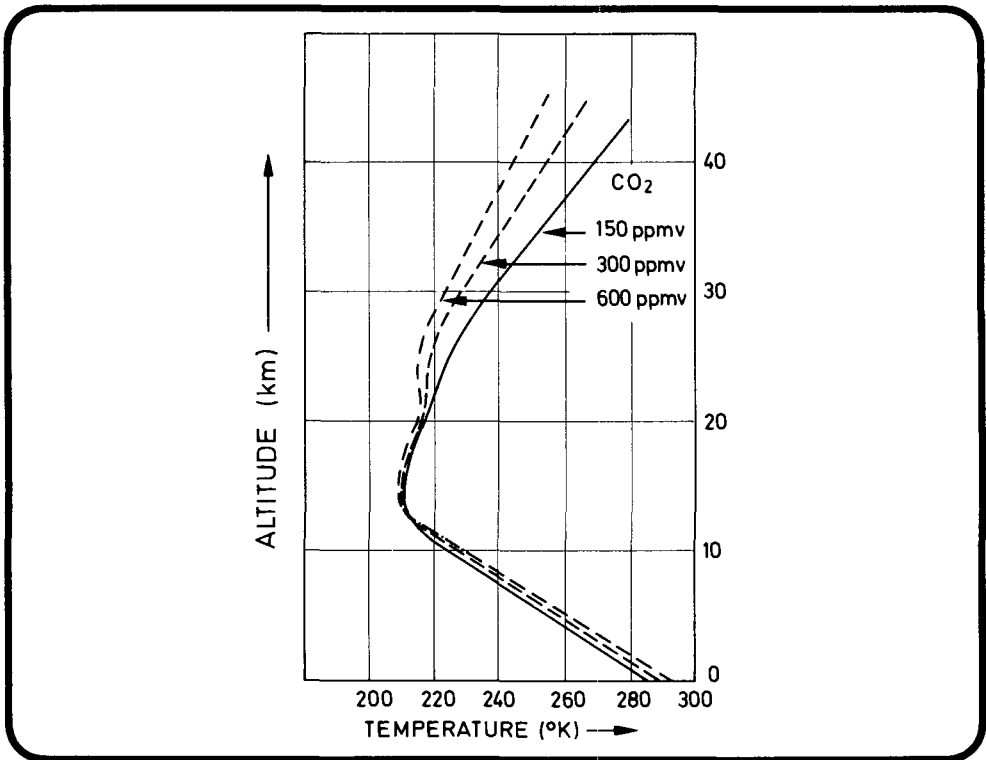
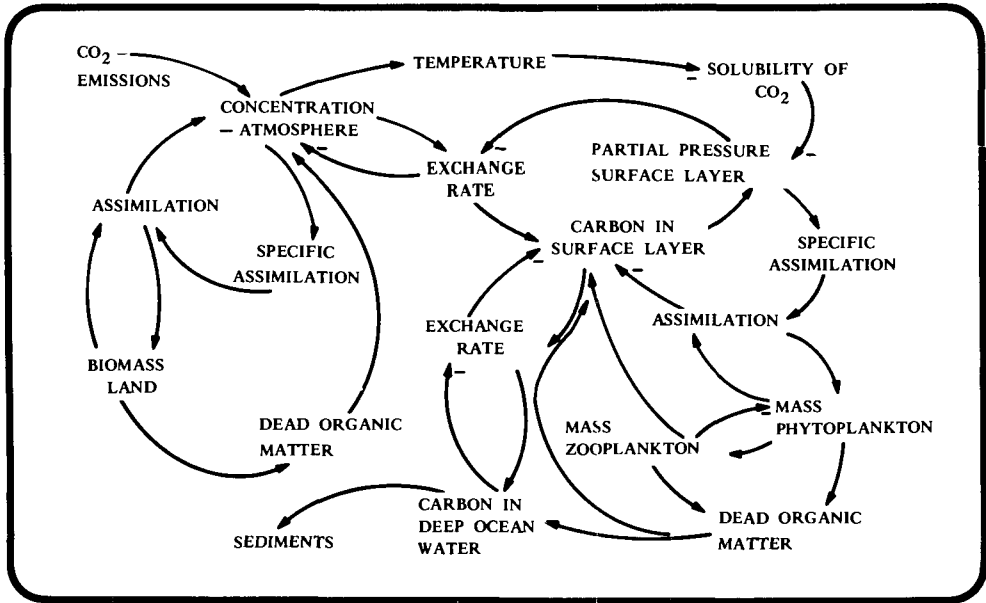


Figure 3. Vertical atmospheric temperature profiles for different CO₂-concentrations Ref. [4].

Figure 4. The loop structure of the carbon cycle.



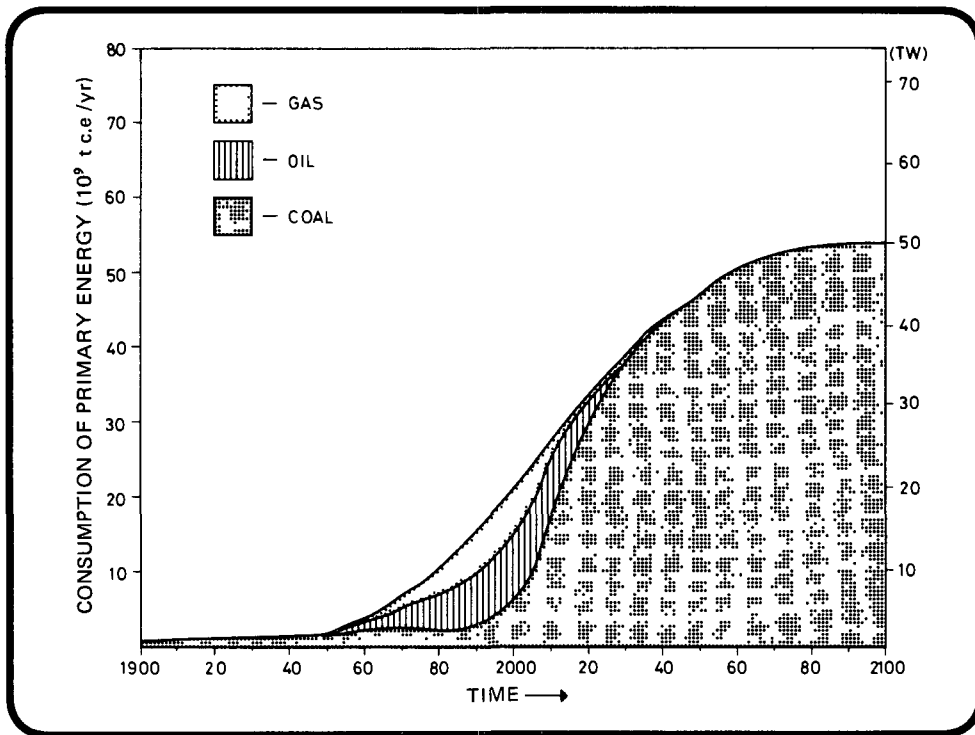
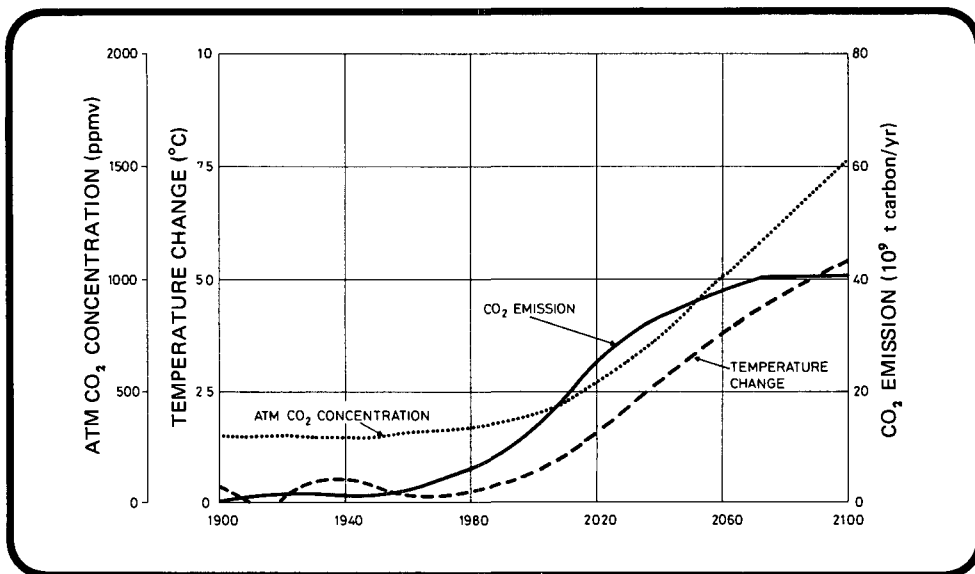


Figure 5. 50 TW fossil fuel energy scenario.

Figure 6. CO_2 -impact of 50 TW fossil fuel scenario.



FUTURE LEVELS OF CARBON DIOXIDE

The model used here considers the global carbon cycle as outlined in the loop-structure of Figure 4. It has been tested against the historical data on the increase of CO₂-concentration, the relative dilution of the carbon-14/carbon-12 isotope ratio (Suess effect), and the carbon-14 decrease in the atmosphere after the cessation of atmospheric bomb testing.

Various future energy scenarios may then be used as input data to the model to calculate expected future carbon dioxide concentrations and resultant temperature changes with regard to those energy strategies.

Let us consider two scenarios which would lead to a total primary energy consumption rate of 50 terawatts (50 000 000 MW) at the end of the next century. For a world population of 10 billion people, such a scenario would provide, on the average, about the per capita energy consumption of European countries. To get the orders of magnitude right, this figure may be compared to the ~ 8 terawatts (TW) we consume today.

50 TW FOSSIL FUEL STRATEGY

Figure 5 shows a scenario where all this energy is supplied by fossil fuels. This would consume almost all coal reserves which have been estimated to be about 4300×10^9 t of coal-equivalent Ref. [9]. Figure 6 shows the model results of such a strategy. Maximum CO₂-emission would be about 40×10^9 t of carbon per year and the CO₂-concentration of the atmosphere is estimated to increase to about 5 times the pre-industrial value. Global average temperature change would be more than 5°C using the data given in Figure 2. If a scenario is used where total consumption is only 30 TW, the concentration would increase to about 4 times the concentration of today by the end of the next century and the global temperature change would be 4°C.

50 TW ENERGY STRATEGY WITH SOLAR AND NUCLEAR

According to present estimates of the greenhouse effect of CO₂, such scenarios would cause major climatic changes. Therefore, a scenario was designed to keep the temperature change below 1°C. It was assumed that in the year 2000, a "CO₂-signal" could be detected and a decision would be taken to reduce CO₂-emissions. Such a strategy is shown in Figure 7 for a 50 TW scenario with solar and nuclear. The results of such a strategy are shown in Figure 8. The maximum emissions of about 10×10^9 t carbon/year occur at the turn of the century. Atmospheric CO₂-concentration would reach a maximum of 430 ppm in 2050 and would slowly decrease again. The maximum temperature change would be 0.6°C above the level of today.

EFFECTS OF CLIMATIC CHANGES

The temperatures given here were derived from calculations on the radiation balance of the atmosphere. However, there is little knowledge on what climatic changes would occur in terms of pressure zones, cloudiness, precipitation, etc. An analysis of the history of climate indicates that indeed in the past major changes in climate occurred very rapidly. Figure 9 shows that these changes were connected with temperature shifts of 2–4°C and occurred with time constants of only a few decades until climate stabilized again on a very different level Ref. [10]. Therefore, it is possible that small changes could trigger off large effects.

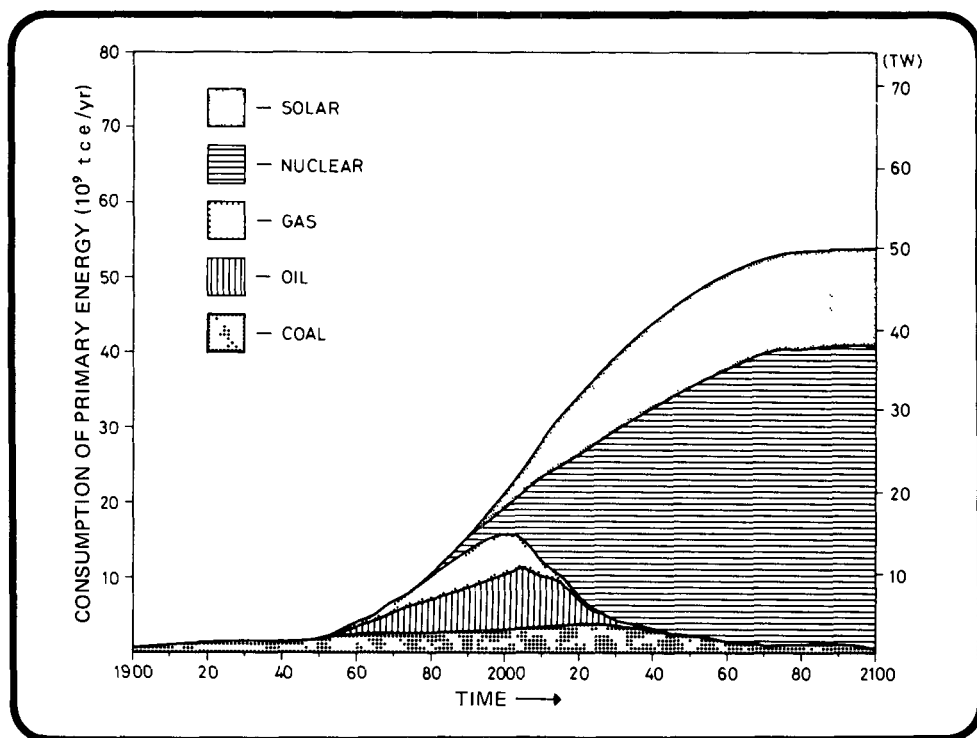
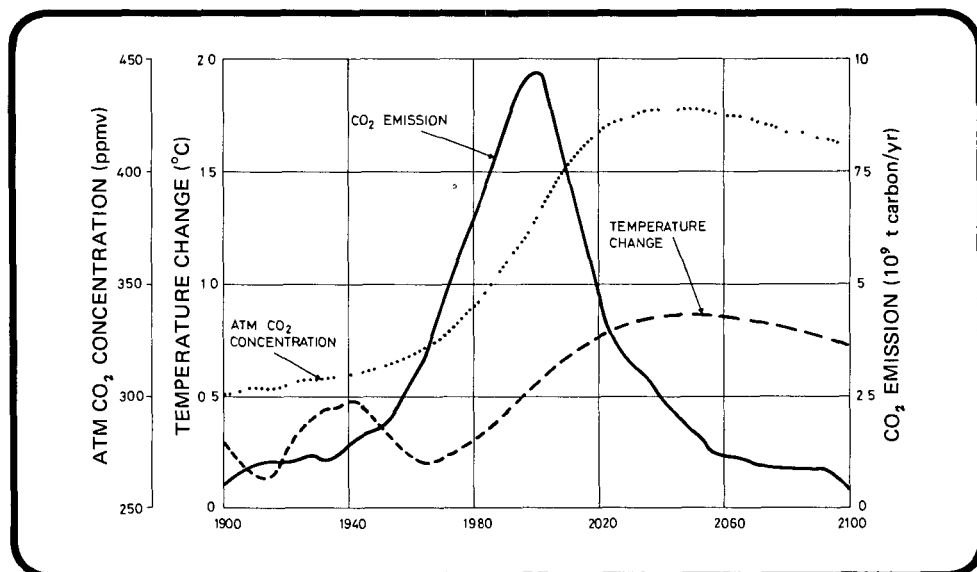


Figure 7. 50 TW energy scenario with solar and nuclear

Figure 8. CO_2 -impact of 50 TW solar and nuclear scenario



The four principal risks of an increase in temperature can be summarized as follows:

a. Impact on World Food Production

It has been estimated that a temperature change of 1°C might lead, on a global average, to a 1–3% decrease in world food production Ref. [11] But this would mean that some parts of the world could be much worse off and others might even improve. In general, it seems to be a problem of adjustment as changes may occur discontinuously, detection would not be immediate and adjustment to new agricultural patterns would take a long time

b. Melting of North-Atlantic Ice Cover

As this ice cover is not very thick, its melting due to temperature increase could occur within a few decades. It has been pointed out earlier that polar regions would be more sensitive to changes in atmospheric carbon dioxide concentration. Such melting would change the albedo significantly and probably would lead to a northern shift of climatic zones

c. Disintegration of West-Antarctic Ice Sheet

This disintegration would raise the level of the oceans by about 4 m. However, the time constant would be in the order of some 1000 years Ref. [12]

d. Melting of Polar Ice Caps

This would raise the sea level by about 60 m. However, the time constant would be some 10 000 years.

CAN CARBON DIOXIDE BE REMOVED FROM THE ATMOSPHERE?

Let us assume that atmospheric CO₂-concentration has doubled to about 600 ppm. For the first scenario this could occur in about 50 years from now. Let us further assume that significant climatic changes have occurred and a world decision has been taken to remove 100 ppm CO₂ from the atmosphere. How difficult is such an undertaking? It would mean that one sixth of the atmosphere would have to be stripped of CO₂.

A back-of-an-envelope calculation shows that assuming an air intake speed of 30 km/h more than 1000 chemical plants, each 100 m high and 1 km long, would have to operate for 30 years to remove that much CO₂.

CONCLUSIONS

These calculations demonstrate the high potential risk of an increase of atmospheric CO₂-concentration. At present, there seems to be no immediate need to reduce fossil fuel consumption. Much more research is needed to understand the carbon-13 data and to understand the possible impacts of climatic changes. Most scientists agree that mankind still has another decade to solve this problem. On the other hand, there seems to be no reason to enhance fossil fuel consumption more than absolutely necessary

It is not the intention of this article to provoke anxieties or fears, but rather to provide more of the information necessary for a rational decision on future energy supply. Such a decision should be based on a comparison of all the risks and benefits of alternative energy systems.

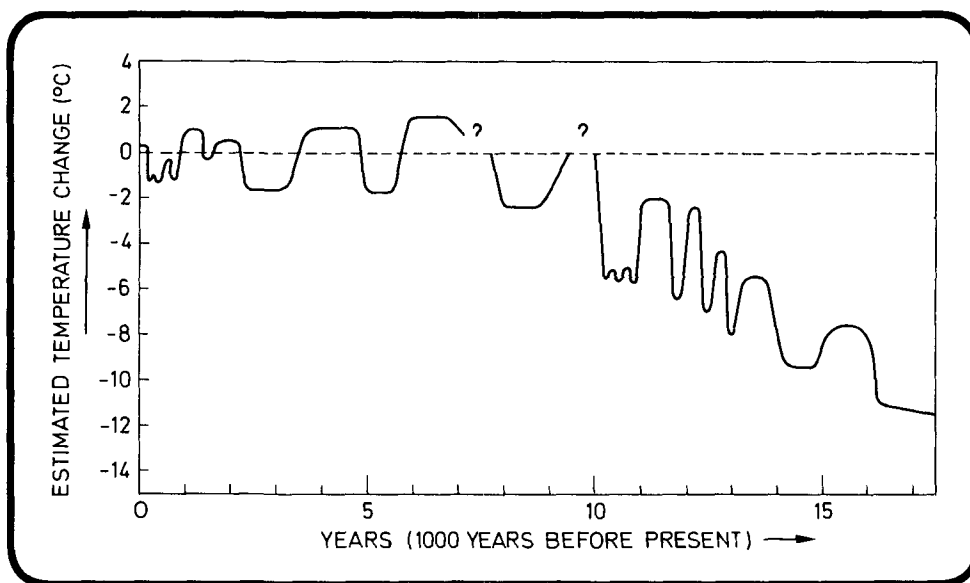


Figure 9. Climatic changes in Central Europe Ref. [10].

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